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LAMINAR BOUNDARY LAYER WITH MODERATE TURBULENCE OF THE INCOMING FLOW

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16. Abstract

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SYNOPSIS /2

This paper gives the results of an experimental study of the structure of a flat plate's laminar boundary layer in the presence of moderate turbulent perturbations. Pressure fluctuations in the incoming flow and vibrations of the plate's leading edge were also checked in the experiments. The evolution of the spectra of root-mean-square values for the pulsations of the longitudinal velocity component and, more specifically, for oscillations with certain fixed frequencies is traced in the boundary layer. It is shown that the structure of the flow is determined by the turbulent motion which occurs near the leading edge of the plate and by its coexistence with three-dimensionally increasing Tollmin-Shlikhting waves.

INTRODUCTION /3

In recent years, the attention of researchers has been drawn to questions about the interaction of turbulent flows with objects. Interest in this complex problem is due not only to purely scientific interest, but also to the practical demands of many sections of the national economy. It is known that in the presence of low levels of external perturbation, the transition to turbulence in the boundary layer of bodies surrounded by a flow occurs as the result of the development of unstable wave motion, which is predicted by the linear theory of hydrodynamic stability and is observed in experiments [1, 2, etc]. However, classical linear stability theory cannot explain a number of the observed facts. It has also been experimentally proven that increasing the external perturbing factors, such as the turbulence of the initial flow, the acoustic vibrations, the surface vibrations, etc., generally produces an earlier transition. Only in the last 15-20 years has the problem of transforming the external perturbations into the pulsed motion of the medium in the boundary layer been formulated (in the terminology of M. V. Morkovin, it is a problem of "susceptibility"). A brief survey of the main (from the point of view of the authors) experimental results which have appeared in various publications and which are connected with the transformation of the turbulent mode (turbulence) of the external flow and with the structure of the motion which occurs in the boundary layer is given below. An extensive bibliography and an analysis of results concerning friction and heat transfer in turbulent flows can be found in [3].

The known results of experimental investigations and the observations of the authors indicate that the structure of the vibrational processes, the development of which finally produces a transition in the boundary layer, depends on the intensity and spectral composition of the external turbulence /4 (see [3, 4]) and also on the conditions of the flow's encounter with the body being studied. As is well-known, this last circumstance is manifested in the formation of a low-pressure peak near the leading edge and, consequently, in the formation and development of Emmons spots or of complete turbulization of the boundary layer [5, 6, 4]. The structure of the turbulent spots which form near the plate's leading edge and their interaction between themselves and with artificially created Tollmin-Shlikhting waves were investigated in [7]. This type of transition to turbulence is one of the important, but undesirable in practice, cases of the interaction of the boundary layer with external turbulence, and it is usually avoided in technical set-ups. When the boundary layer's transition is studied experimentally under laboratory conditions, this regime is easily eliminated by the use of an adjustable flap [5, 9].

Analyzing the known experimental work which has been carried out on flat plates without longitudinal pressure gradients, one can conditionally distinguish three situations with regard to the structures of the pulsed motion in the laminar boundary layer which appear under the influence of external turbulence:

1. A laminar boundary layer with a low degree of flow turbulence, $\varepsilon < 0.1\%$;
2. A laminar boundary layer with high-intensity turbulent pulsations, $\varepsilon \gtrsim 0.7\%$.
3. A laminar boundary layer with a moderate level of turbulence, $0.1\% \leqslant \varepsilon < 0.7\%$.

Let us again emphasize the conditionality of the limits which are indicated.

A laminar boundary layer with low levels of turbulent perturbation of the external flow ($\varepsilon < 7\%$) is distinguished by the fact that the transition to turbulence is due to the appearance, development and subsequent failure of the natural oscillations of the boundary layer (the Tollmin-Shlikhting waves), the evolution of which is described, in the first phases, by linear

stability theory. This regime was first investigated by Schubauer and Skramstad [1]. It was later shown (see [8, 6, 9, 10, etc]) that the transition to turbulence is preceded by rate pulsations when the level of natural background perturbations is low ($\varepsilon < 0.1\%$). A certain frequency packet in the pulsation spectrum is singled out and amplified. The dimensionless frequencies of the vibrations and the phase velocities correspond to the regions of /5
instability which are calculated from linear theory. The profiles of the longitudinal components of the velocity pulsations, which were measured in a narrow band of frequencies, have features which are characteristic of unstable Tollmin-Shlikhting waves (see [10]). The amplitudes of these waves generally reach values of 1-4% before the transition to turbulence.

In the presence of high turbulence ($\varepsilon \geqslant 0.7\%$), the pulsed processes in a laminar boundary layer are basically different from the processes which take place in the presence of low-intensity turbulence, and they have a number of characteristics:

a) The spectrum of the velocity pulsations is continuous. Low-frequency vibrations, which should be attenuated according to the linear theory of hydrodynamic stability, predominate and are amplified [6, 13, 14]. At the same time, vibrations which are unstable according to the theory are weakened;

b) The profiles of the longitudinal components of the velocity pulsations, which are measured in a narrow band of frequencies, differ from the distribution of the root-mean-square amplitudes in the Tollmin-Shlikhting waves and have a natural maximum [14]. The maximum of an amplitude which is integrated over the spectrum of velocity pulsations corresponds to the coordinate $\eta = y \cdot \sqrt{U_\delta / \nu \cdot x} = 2 - 2.3$ [13, 14, 3, 4];

c) At the pulsation maximum, an amplitude which is integrated over the spectrum increases as the Reynolds number increases, reaching 7-9% [6, 13, 14];

d) Despite the high pulsation level, the distributions of the mean velocities in the laminar boundary layer are similar to a Blazius profile [14, 4]. However, experiments are known in which the turbulence of the external flow exerted an influence on the mean flow [3, 6, 13];

e) The scales of the three-dimensional transient motion inside the boundary layer along coordinates which are orthogonal to the direction of the main flow are commensurate with its thickness. This measures the spatial correlations of the longitudinal components of the velocity pulsations along a normal to the surface in the transverse direction also [4];

f) The drift rate of turbulent structures in the boundary layer is 0.5-0.6 of the external flow's velocity [14]. The transition to turbulence occurs with the formation of turbulent spots [14].

These traits make it possible to assume that the Tollmin-Shlikhting /6 waves do not play an important role in the laminar-to-turbulent transition when the turbulence of the external flow is high. The experimental fact that the basic laws governing the described pulsed motion are also observed in an accelerated flow [4], where the Tollmin-Shlikhting waves should be damped, speaks in favor of this opinion.

We should mention here that [7] presence an inaccurate treatment of questions connected with the effect of a high level of turbulence on the boundary layer. It says on page 11: "In [13]* the boundary layer is assumed to be integrated, without separation of the turbulent spots, and is called pseudolaminar when there is a high degree of turbulence in the incoming flow. In our opinion, such a treatment makes it impossible to investigate the structure of a given flow in detail." This is a one-sided view of the problem. The authors of [7] are obviously not familiar with [14], where results are given which indicate the appearance of turbulent spots only in the later stages of the development of a laminar (or pseudolaminar) boundary layer.

The experimental data from work carried out with moderate turbulent pulsations (0.1% 1 0.7%) are somewhat contradictory. Three-dimensionally increasing oscillations, the frequencies of which correspond to unstable Tollmin-Shlikhting waves, were isolated in [8, 6] based on the spectral analysis of the signal from a hot-wire anemometer in the part of the boundary layer next to the wall. However, the other characteristics of this wave motion are not given in [8, 6].

Klebanov [11]** has shown that outside turbulence leads to amplification of low-frequency pulsation in the boundary layer, which are stable according to linear theory. This result was repeated in [6]. The profiles of the root-mean-square velocity fluctuations in the layer have a single maximum. Klebanov connects the shape of the profile with the instability of the boundary layer's thickness and calls it "the breathing mode". The maximum of the fluctuation amplitude integrated over the spectrum is located at $\eta \cong$

* The reference number is given in accordance with the reference guide in this paper.

** The results of [11] and [15] are taken from [12].

$\cong$ 2.3, and its value increased by up to 5% at a distance from the plate's leading edge. Moreover, small scales were indicated for the pulsed motion, based on the spatial correlations measured along the coordinates perpendicular to the direction of the flow. Tollmin-Shlikhting waves were not found on a smooth plate in a turbulent flow. /7

Low-frequency unstable motion whose amplitudes reached 12% and were similar to Klebanov's data was also observed in the experiments of Arnal and Juillen [15]. Tollmin-Shlikhting waves which were small in comparison with the low-frequency oscillations of amplitude were noted only for the lowest degree of turbulence ($\mathcal{E}$ = 0.1%).

The data from J. M. Kendall's paper [12] confirms the existence of intense low-frequency motion in the boundary layer. In this case, the amplitude reaches 6%. The profiles of the root-mean-square amplitudes has a single extremum, the coordinate of which corresponded to $\eta \cong 2.3$ for an amplitude which was integrated over the spectrum. The profile of the root-mean-square fluctuation values gives a value of $\eta \cong 4$ for the maximum in a narrow band of frequencies. Measurements of the spatial correlations in the transverse direction and visualization of the flow revealed structures with small cross-sectional scales in the flow, as in [11]. The existence of Tollmin-Shlikhting waves which are weak in comparison with the large amplitudes of the main motion is noted.

Thus, in a flow with a moderate level of turbulent perturbation, the pulsed motion in the laminar boundary layer reveals traits which are characteristic of flows with high turbulence, and the Tollmin-Shlikhting waves are of low intensity (following [11, 12, 15]).

Meanwhile, results indicate that the Tollmin-Shlikhting waves determine the transition to turbulence [8, 6], but the boundary layer has been inadequately investigated. Finally, there is a discrepancy in the position of the maxima in the distributions of the root-mean-square amplitudes of the longitudinal component's pulsations as measured in the filters' wide and narrow transmission bands [12].

The purpose of the experiments presented here is to obtain additional information and to deepen our understanding of the pulsed motion's structure and of the role played by Tollmin-Shlikhting waves in a laminar boundary layer under the influence of moderate turbulence of the incoming flow.

The results of the experiments were reported at the Third All-Union /8

Conference on Problems of Turbulent Flows (Zhdanov, Province of Melekino, 1986). The authors were able to discuss these experiments (with advantage) with A. N. Sekundov and his colleagues in 1987.

EQUIPMENT, INSTRUMENTS AND EXPERIMENTAL CONDITIONS

The experiments were conducted in the T-324 low-turbulence wind tunnel at the Institute of Theoretical and Applied Mechanics of the Siberian Department of the USSR Academy of Sciences. A flat plate made of D16AT aluminum alloy with a thickness of 6 mm and dimensions of 1000 mm x 2000 mm in the plane was used [9]. The plate's nose, which was thinner (4 mm over a length of 60 mm), was rounded over a radius of $r = 2$ mm. Flaps were placed on the trailing edge of the plate. The flaps' angle of deflection and, consequently, the pressure distribution in the vicinity of the leading edge, were controlled from outside the tunnel's working area. The pressure downstream ($X > 50$ mm) was determined with the help of a static-pressure probe having a diameter $d = 1$ mm and located at a distance of $Y = 5$ mm above the plate's surface. A grid of synthetic filaments was used to increase the turbulence of the flow. The elements of the grid were 5-6 mm square.

A set of thermoanemometric equipment from DISA was used in the experiments. The equipment included a linearizer and miniature hot-wire anemometers with a single sensing element made of Wollaston filament which were prepared in accordance with [16]. The dimensions of the working element were $d \times l = 3$ microns x 0.4 mm. Spectral analysis of the signals and measurements at fixed frequencies were carried out with the help of FAT-1 heterodyne analyzers from Rohde & Schwarz, where the filter's transmission width was $\Delta f = 4$ Hz. Equipment from Brüel & Kjer and RFT was used to measure the vibrations of the plate's leading edge and the pressure fluctuations in the flow.

As in [9, 10], the hot-wire anemometer's detector and the static-pressure probe were displaced with an accuracy of 0.02 mm along a normal to the plate's surface (the y-axis) and of 1 mm along the longitudinal coordinate (the x-axis) by means of a traversing probe.

The experiments were conducted with an incoming flow whose velocity was $U_\infty \simeq 18.1$ m/s. The region which was investigated included the plate's leading edge and extended 1500 mm downstream and along a normal to the model's surface ($0 \leqslant Y \leqslant 40$ mm). /9

Distributions of pressure in the form of the coefficients $C_p = 2(P-P_\infty)/\rho \cdot U_\infty^2$ are shown in figures 1a and 1b as functions of the coordinate X and of the Reynolds number Re^*. Here P_∞ and U_∞ are the pressure and velocity in the reference section at X = -800 mm; P is the pressure; ρ is the density; $Re^* = 1.72\sqrt{U_\delta \cdot X/\nu}$; U_δ is the velocity at the edge of the boundary layer; ν is the kinematic viscosity. The open circles in figure 1 denote the results of measurements at low turbulence (without the grid), and the dark circles denote measurements for a turbulence of $\varepsilon_u = 100 \cdot u'/U_\infty = 0.5\%$ (with the grid in place).

Figure 1b gives the experimentally determined values of the form parameter $H = \delta_1/\delta_2$, where δ_1 is the displacement thickness and δ_2 is the momentum thickness. The profiles of the mean velocity in the boundary layer differ from the Blazius profiles at the leading edge and at $X \geqslant 1100$ mm.

The spectra of the root-mean-square pressure fluctuations were recorded in the reference section at X = -800 mm, where a capacitor microphone with an anti-wind hood was placed. They are shown in figure 2. Line 1 represents the data for elevated flow turbulence; line 2 represents the results of measurements made without a turbulizing grid. There are no qualitative changes in the spectral composition of the fluctuations. An increase of the amplitude of the pressure fluctuations is observed at frequencies of less than 150 Hz.

The spectra of the root-mean-square vibrational accelerations of the plate's leading edge (see figure 3) with the grid in place (line 1) and without it (line 2) are identical.

The root-mean-square amplitudes of the fluctuations of the velocity's x-component in the incoming flow (the section X = -100 mm) remained almost constant for frequencies of $f \leqslant 250$ Hz when the grid was used, and then they decreased linearly for frequencies up to 2 kHz. Discrete frequencies were not observed in the spectra (fig. 4). The integral root-mean-square intensity of the fluctuations of the velocity's x-component (ε_u) was 0.5% in the frequency interval of $2-2 \times 10^4$ Hz. The spectral composition of the fluctuations in the incoming flow without a turbulizing grid can be found in [9, 10].

Thus, considering the measurements and data which are given [9, 10], one can conclude that the grid creates mainly turbulent fluctuations of the flow.

RESULTS OF EXPERIMENTS

It was shown in [1, 8, 6, 9] that vibrations which correspond to the frequency band of unstable Tollmin-Shlikhting waves occur and are amplified in the boundary layer when the level of the background perturbations is low. The data in figure 5 illustrate the change of the spectral composition of the x-component of the velocity fluctuations in the boundary layer under the influence of an elevated level of turbulent perturbations when $Re^{*} = 2140$ ($U_\delta = 17.9$ m/s, X = 1400 mm) and the relative mean velocity is $\bar{U} = U/U_\delta \approx 0.4$. Here the solid line I-II shows the frequency range of the unstable vibrations predicted by linear stability theory. One can see that the amplitudes of some of the unstable waves increase by more than a factor of ten. In this case, oscillations with frequencies which lie near the second branch of the neutral line have been amplified the most.

Distributions of the root-mean-square fluctuation amplitudes u'_f at a frequency f = 110 Hz (the frequency parameter is $F = 2\pi f \cdot \nu / U_\delta^2 = 34 \times 10^{-6}$) were obtained along a normal to the plate's surface for this number Re^{*} (fig. 6). The Blazius variable $\eta = Y \cdot \sqrt{U_\delta / X \cdot \nu}$ lies on the y-axis. Amplification of the vibrations which varies as a function of η is observed when there is a moderate degree of turbulence in the external flow. The greatest changes occur near the outer edge of the boundary layer.

The evolution of the spectra of the longitudinal velocity fluctuations in the boundary layer when $\bar{U} = 0.4$ and the distance from the leading edge is increased are shown in figure 7. The spectra of the velocity fluctuations u'_f in the incoming flow (X = -100 mm, Y = 40 mm, line 1) and outside the boundary layer at X = 1500 mm and Y = 40 mm (line 2) are given here. The spectra of the fluctuations of u'_f are smooth. They have an almost constant amplitude for frequencies up to $f \cong 200$ Hz and give a picture of the degeneration of turbulence in a free flow. Inside the boundary layer, the spectra remain continuous in the initial stages of development (X < 500 mm). Their restructuring is connected with the growth of the lower frequencies and with the attenuation of the higher frequencies, which is analogous to what occurs when a free flow's level of turbulence is high [6, 13, 14, 4]. However, a wide band of amplified frequencies is observed in the spectrum further downstream. Some vibrations with greater amplification can be isolated in this band. The amplified frequencies correspond to the theoretical region of instability

The profiles of u'_f (the components of the velocity fluctuations for a series of frequencies) were measured in order to ivnestigate the dynamics of the appearance and development of vibrational motion in the boundary layer as the Reynolds number increases. Frequencies of 40, 85, 110, 130, 140 and 160 Hz were chosen. At a flow rate of $U_\infty \approx 18$ m/s, these frequencies corresponded to the dimensionless parameters $10^6 F = 12.4, 26.3, 34, 40.2, 43.3$ and 49.4. All the vibrations which were chosen, with the exception of the fluctuations with a frequency of f = 40 Hz, fell into the range of unstable frequencies during their development downstream (fig. 8). The profiles of the fluctuations of the velocity's x-component (u'_f) at the selected frequencies were obtained with a spacing of $\Delta X = 100$ mm, and the vicinity of the leading edge ($X < 50$ mm) was studied in more detail.

Figure 9 gives the profiles of u'_f in the section X = 100 mm ($Re^* = 557$) for all the selected frequencies. This section is located in a region of the boundary layer where all the vibrations should be damped, according to the classical linear theory of hydrodynamic stability. The data which are given make it possible to ascertain the following:

- the distribution of the fluctuations u'_f across the boundary layer does not have characteristics in commom with the amplitude function of the Tollmin-Shlikhting waves;
- the fluctuations of the velocity's x-component achieve their maximum inside the boundary layer. The amplitude of this maximum decreases as the frequency increases. We should recall that the amplitudes of the frequencies under investigation are the same outside the boundary layer (see fig. 7);
- the position of the fluctuation maximum shifts toward the outer edge of the boundary layer as the frequency increases. The coordinate which corresponds to the maximum values of u'_f for a given Reynolds number is located in the region $2 \leqslant \eta_{max} \leqslant 3$.

Thus, one can conclude that basic features which are characteristic of the boundary layer in a strongly turbulized flow appear in the region of the boundary layer which is stable according to linear theory in the presence of moderate turbulent perturbations of the external flow [13, 14].

Figure 10 shows the profiles of the fluctuations u'_f for the section X = = 1500 mm, which corresponds to the largest Reynolds number – $Re^* = 2240$.

For this Reynolds number, the selected frequencies completely cover the range of vibrations which are unstable according to linear theory. It follows from a comparison with the data from figure 9 that:

- the fluctuation distributions have been transformed and have acquired a form which is characteristic of unstable turbulent waves which develop in the boundary layer when there is a naturally low level of external perturbation [see 9, 10]; /12
- the fluctuations of the velocity's x-component also achieve maxima within the boundary layer. However, oscillations with frequencies of 130 Hz and 140 Hz are amplified the most. These oscillations correspond to the vicinity of the second branch of the neutral line for a given Re^* (fig. 8);
- the position of the downstream maxima in the profiles of u'_f correspond to values of the Blazius variable η_m which are characteristic of unstable turbulent waves;
- the profiles of the fluctions u'_f for $\eta \geqslant 3.5$ are inflated in comparison with the data [9, 10] for a low level of perturbation.

Thus, the most important characteristics of the boundary layer in a flow with a low level of turbulence (the isolation and amplification of unstable Tollmin-Shlikhting waves) appear in an unstable (according to linear theory) flow region in the presence of moderate turbulent perturbations.

Let us now follow the laws governing the formation of the profiles of the velocity's longitudinal fluctuations u'_f in the case of oscillations with a frequency of $f = 140$ Hz (figures 11a and 11b). In the region of flow which linear theory says is stable, the maximum amplitude of the fluctuations decreases weakly according to the distance from the plate's leading edge ($X > 50$ mm), and the maximum is shifted toward the outer edge of the boundary layer. An intense attenuation (by almost an order of magnitude) of the amplitude of the velocity fluctuations takes place in the region of the boundary layer which lies next to the surface of the plate.

Further downstream at $X > 500$ mm, where the Reynolds numbers exceed the values which correspond to the first branch of the stability's neutral line, an intense growth of the fluctuations occurs when $\eta < 2$. Weak changes of the profile of u'_f occur in the outer part of the boundary layer. The position and value of the amplitude maximum for $\eta = 3.5 - 4$ hardly changes up to $X = 1190$ mm.

The next stage of the evolution is characterized by the growth of the oscillations in both the inner and outer sections of the boundary layer and by the shifting of the upstream maximum toward larger values of η, reaching a value of $\eta = 5.5$. The shape of the fluctuation profile is similar to the amplitude distribution in an unstable turbulent wave with small natural perturbations [9, 10], but it has a comparatively inflated outer region. /13

The profiles of the amplitude fluctuations for the remaining frequencies, which were measured in the filter's narrow transmission band, display qualitatively similar behavior, but the beginning of the intense growth in the inner layers of the boundary layer was connected with Reynolds numbers which correspond to the first branch of the stability's neutral line. This corroborates the data from figure 12, which gives the growth curves for three frequencies: f = 40 Hz, 110 Hz and 140 Hz ($10^6 \cdot F = 12.4$, 34 and 43.3). $J_i = \ln(u'_f/u'_{f_o})$ lies along the Y-axis. The index i = 1, 2, 3 indicates the number of the maximum in the distribution of the amplitudes of the longitudinal velocity fluctuations along a normal to the plate's surface (see sketch): u'_f is the current amplitude, and u'_{f_o} is the minimum measured value of the fluctuations for the corresponding maximum. Figure 12a gives the results for maximum 2. The theoretical curves for the amplification of the Tollmin-Shlikhting waves, which were calculated for the Blazius boundary layer and for the frequency parameters $10^6 \cdot F = 30, 40$ with allowance for nonparallel flow, are also shown here [17]. From a comparison of the experimental and theoretical curves at Reynolds numbers where the profiles of the mean velocity are similar to the Blazius profiles, one can see that the increments of the unstable turbulent waves do not differ greatly. We should mention that pulsations with f = 40 Hz begin to grow without reaching the first branch of the classical neutral curve. This is apparently due to positive pressure gradients.

Figure 12b gives the growth curves for the outer maximum 3. The functions are radically different. First of all, the velocity fluctuations are amplified for all the frequencies which were investigated in the vicinity of the leading edge, which has a dimension $\omega \cdot X/U_\infty \sim 1$ ($\omega = 2\pi \cdot f$, X is the distance from the leading edge to the points "M" (see fig. 12b)). Further downstream, the oscillations are damped much more weakly than the linear theory for Tollmin-Shlikhting waves says they should be. The behavior of the curves in a neutral-stability loop probably reflects the struggle of two processes. On one hand, the total amplitude is determined by the turbulent motion, which appears in the vicinity of the plate's leading edge and is weakly attenuated downstream. On the other hand, unstable waves are stimulated and amplified in the boundary layer. Initially, this stabilizes the amplitudes of the oscillations (in the case of $f = 140$ Hz for $Re^* \geqslant 1150$), but there is also growth later.

Questions about the three-dimensional nature and scales of the external turbulent perturbations, of the motion created by them inside the boundary layer and of the boundary layer's interaction with unstable waves are touched on only lightly here. These questions should play an important role when there is a high degree of turbulence, and at later stages of the boundary layer's development in flows with moderate levels of turbulent perturbation. /14

CONCLUSIONS

The investigation which was carried out and the known results make it possible to formulate two basic assertions:

1. Given a moderate degree of turbulence in the incoming flow, the structure of the flow in the boundary layer is determined by the coexistence (or interaction) of two processes. One of them is due to the instability of the boundary layer, as a result of which external perturbations are engendered and three-dimensionally increasing waves (Tollmin-Shlikhting waves) develop. The other is connected with the conversion of external turbulent fluctuations into turbulent motion in the boundary layer. This motion is stable in an unstable (according to the classical linear theory of hydrodynamic stability) range of Reynolds numbers, and its characteristics differ from those of Tollmin-Shlikhting waves.

2. This stable turbulent motion of the boundary layer is formed in the vicinity of the plate's leading edge. The approximate size of the region where the turbulent motion is formed is $\omega \cdot X/U_\infty \sim 1$.

Fig. 1. 1 - X, meters

Fig. 2. 1 - f, Hz

Fig. 3. 1 - f, Hz

Fig. 4. 1 - f, kHz

Fig. 5. 1 - f, Hz; 2 - with the grid; 3 - without the grid

Fig. 6. 1 - without the grid; 2 - with the grid

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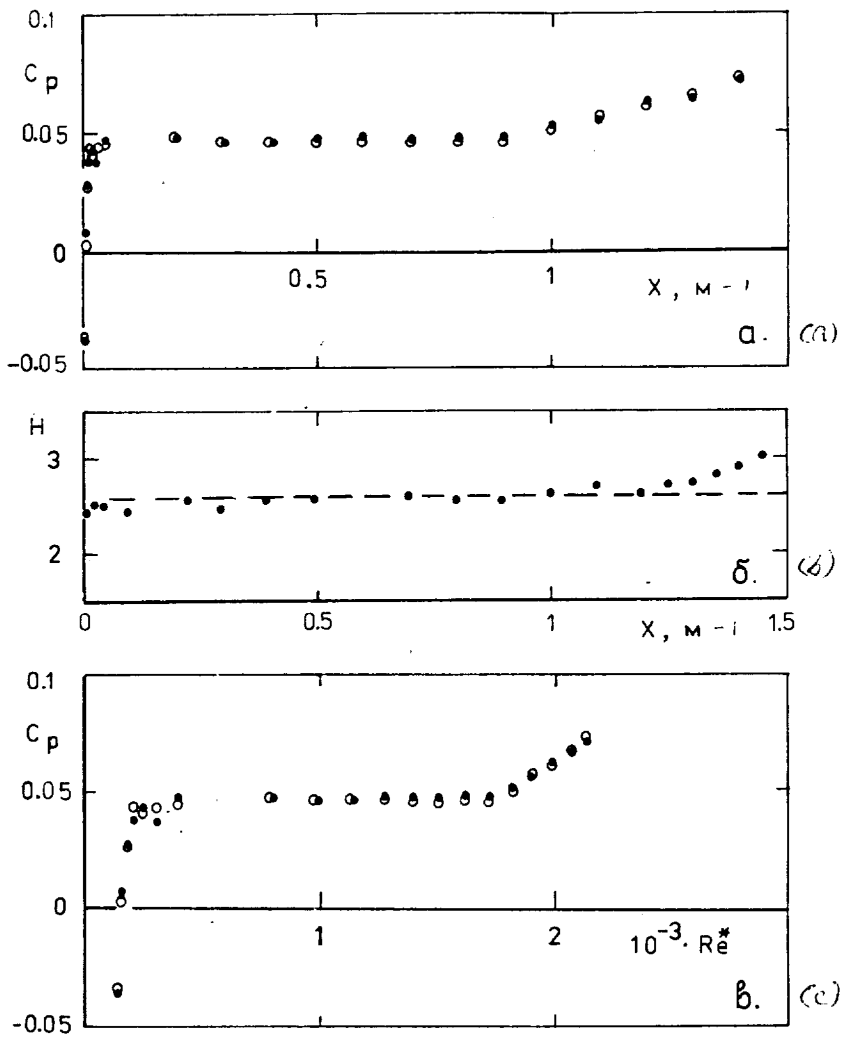


Fig. 1. 1-X, meters

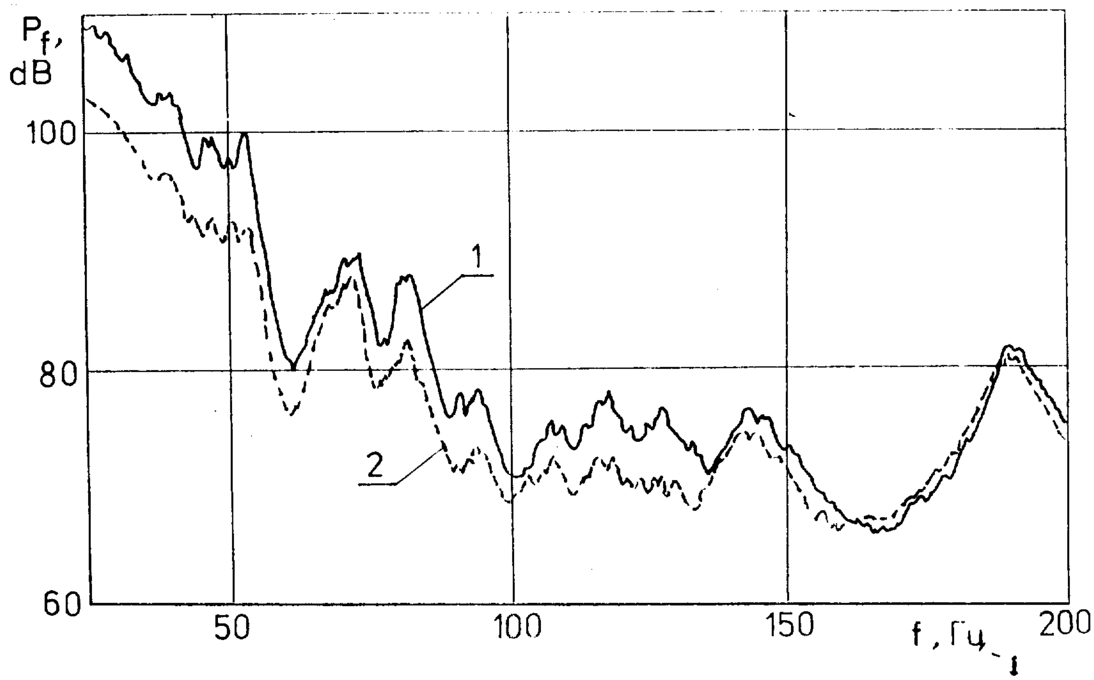


Fig. 2. 1-f, Hz

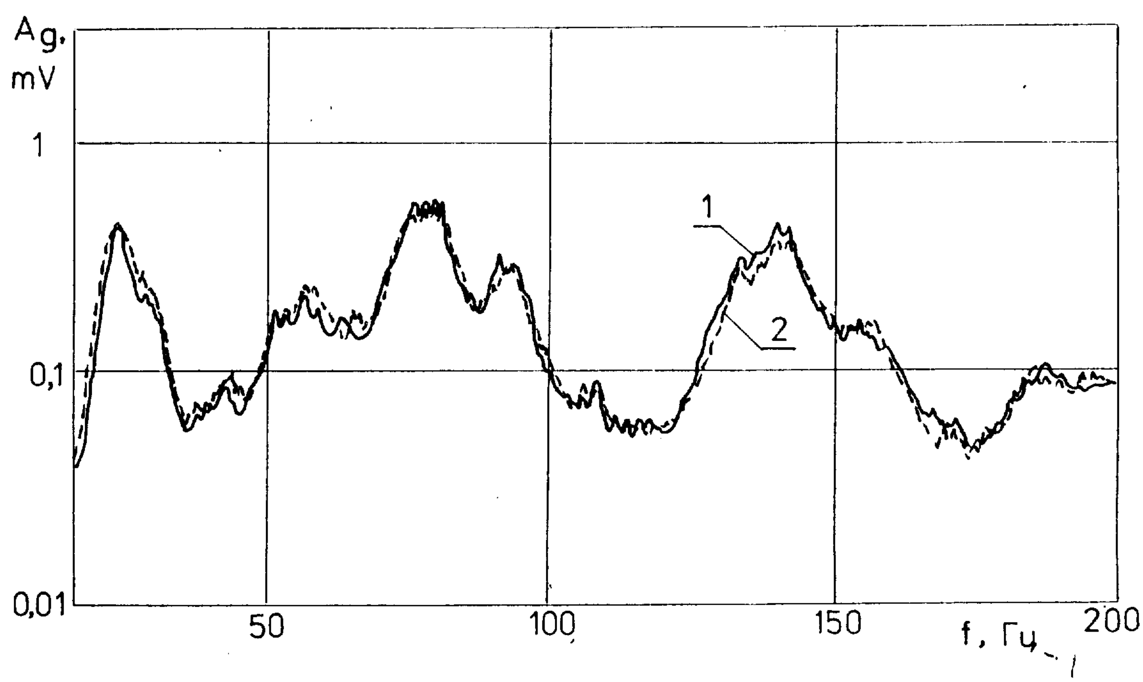


Fig. 3. 1-f, Hz

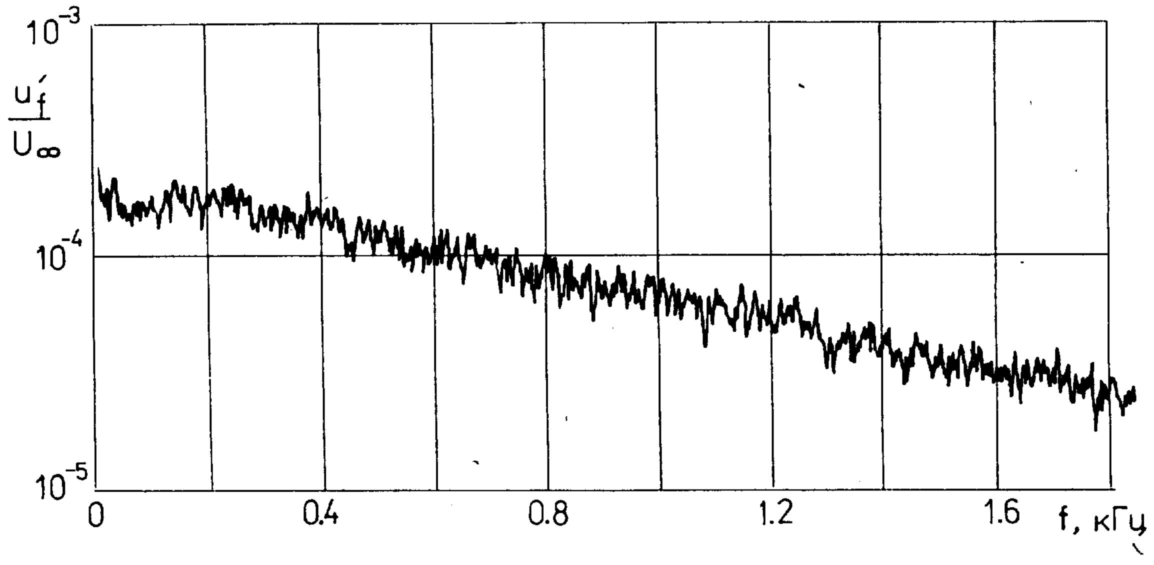
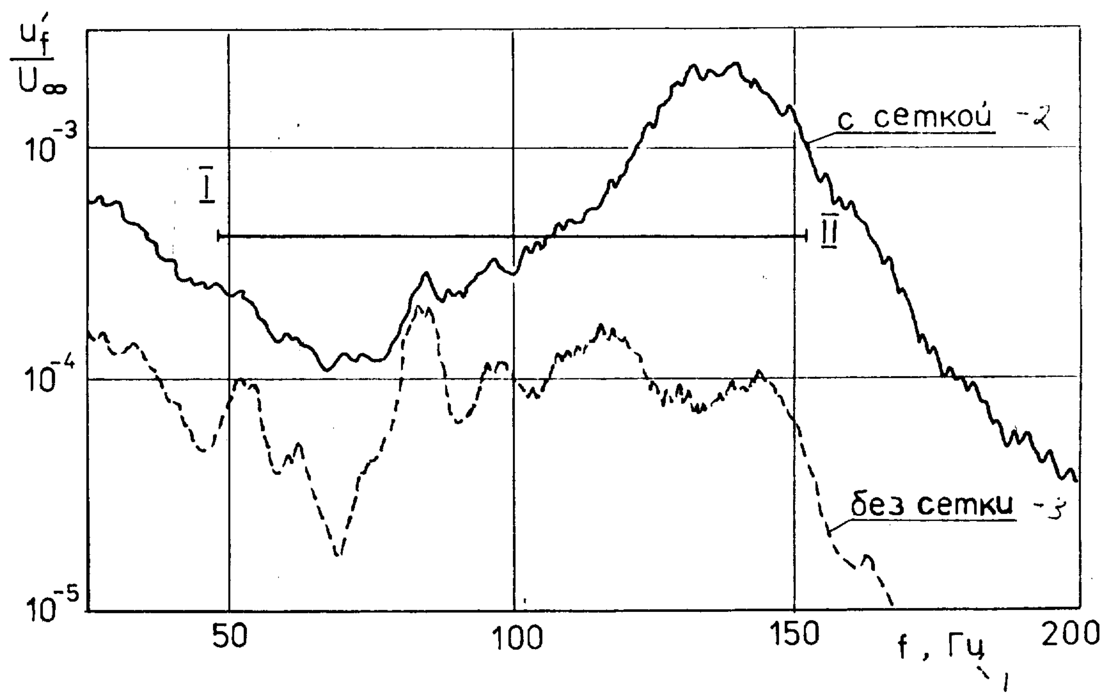
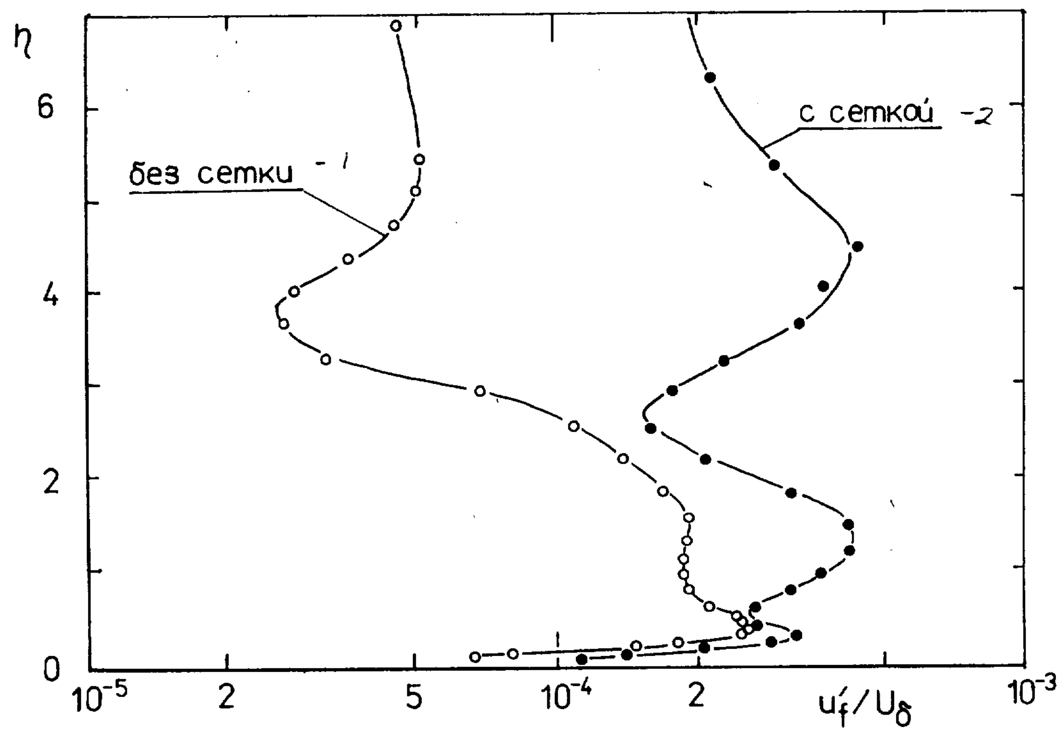


Fig. 4. 1 - f, kHz



2 - with grid; 3 - without the grid



6. 1 - without the grid; 2 - with the grid

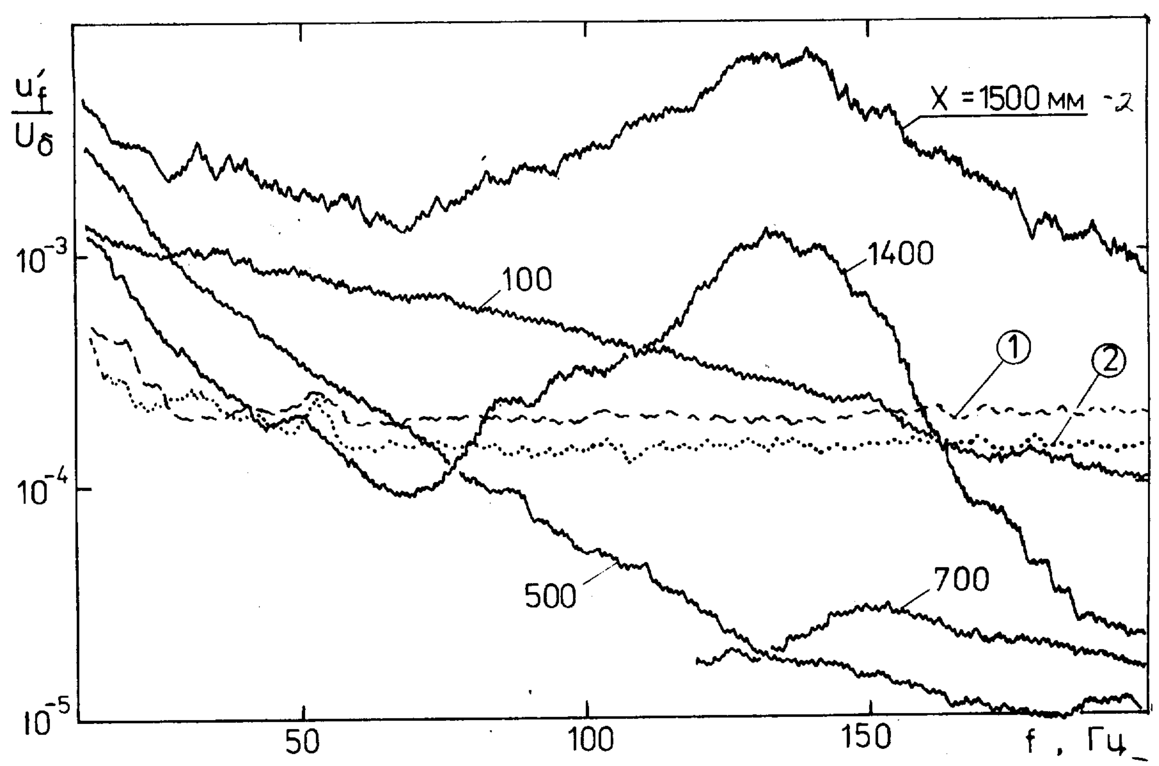


Fig. 7. 1 - f, Hz; 2 - X = 1500 mm

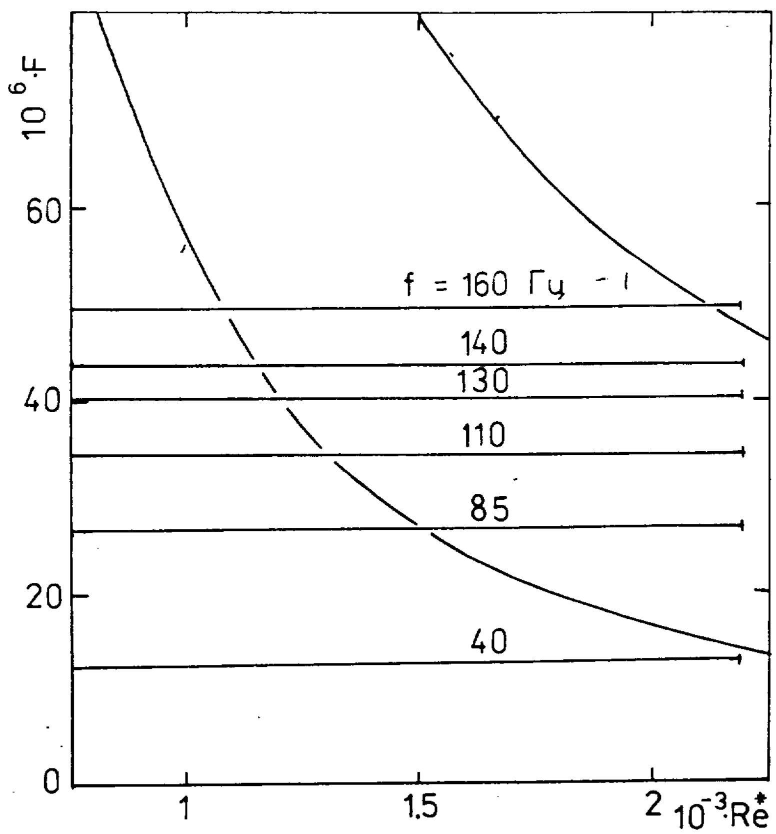


Fig. 8. 1 - f = 160 Hz

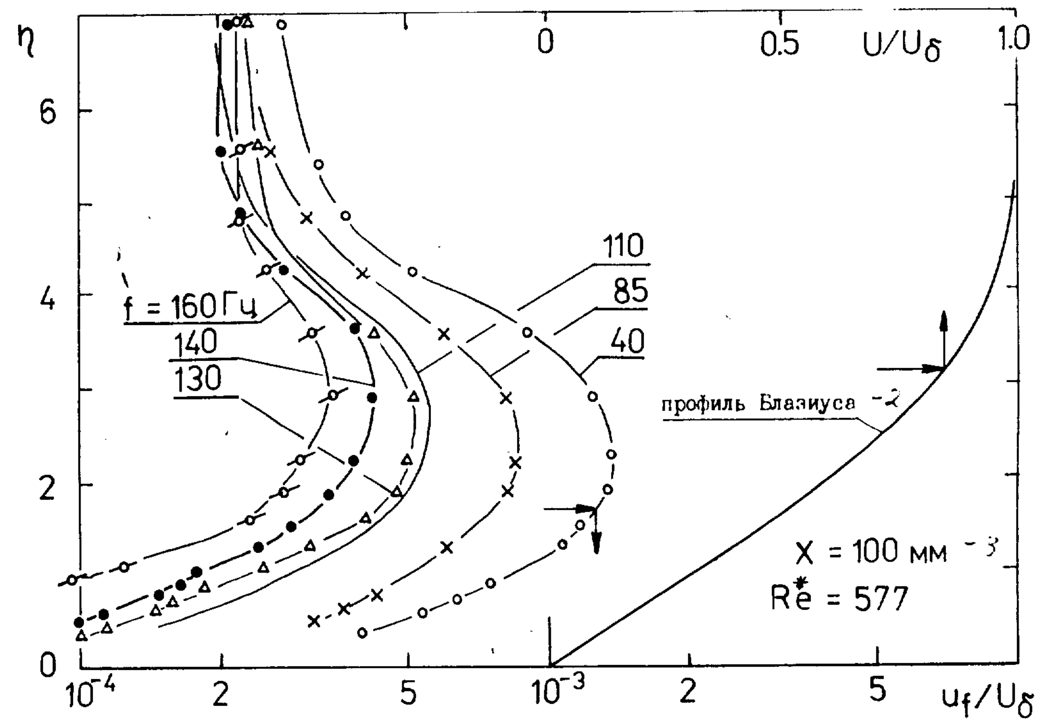


Fig. 9. 1 - f = 160 Hz; 2 - Blazius profile; 3 - X = 100 mm

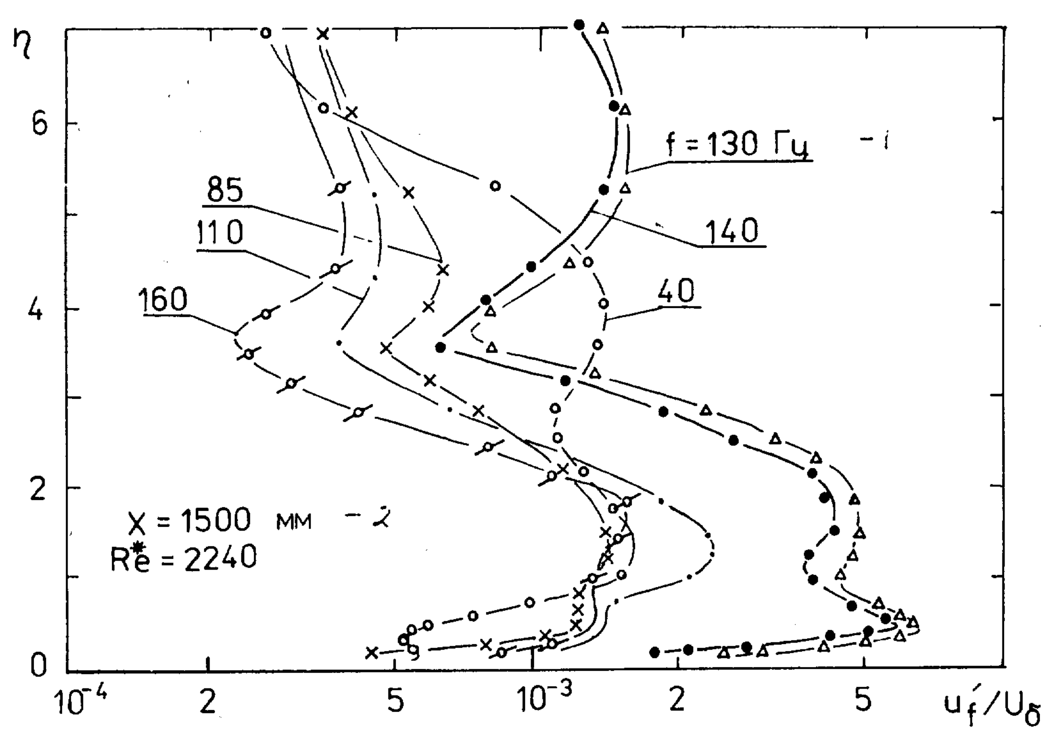


Fig. 10. 1 - f = 130 Hz; 2 - X = 1500 mm

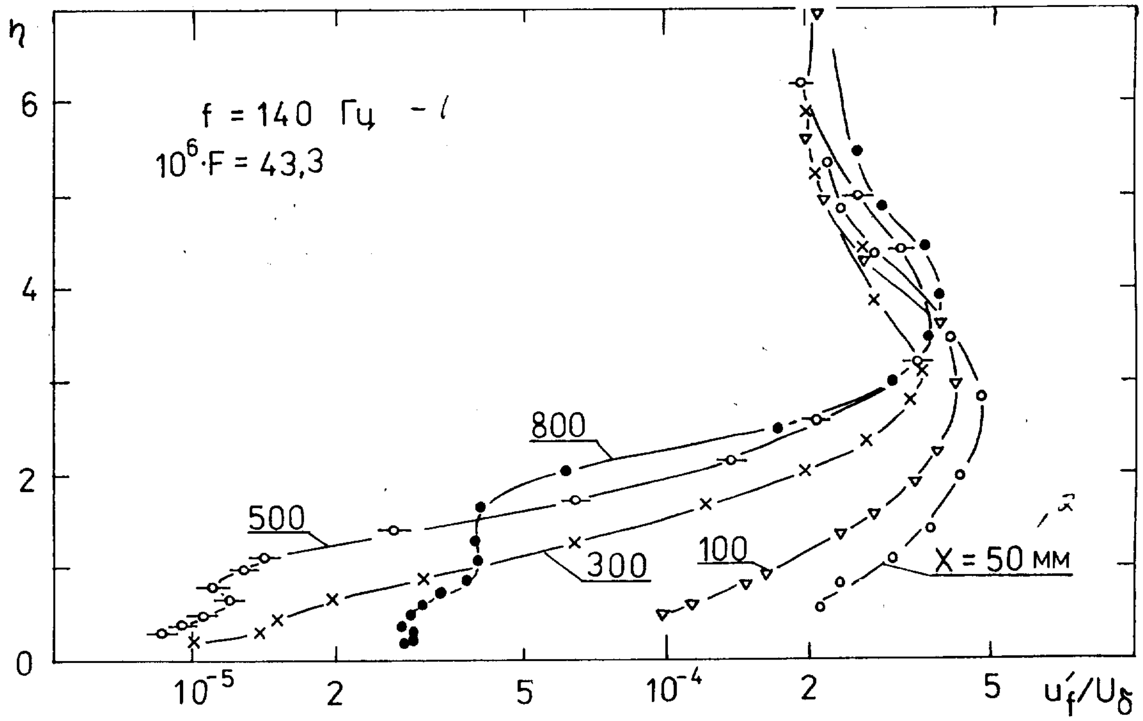


Fig. 11a. 1 - f = 140 Hz; 2 - X = 50 mm

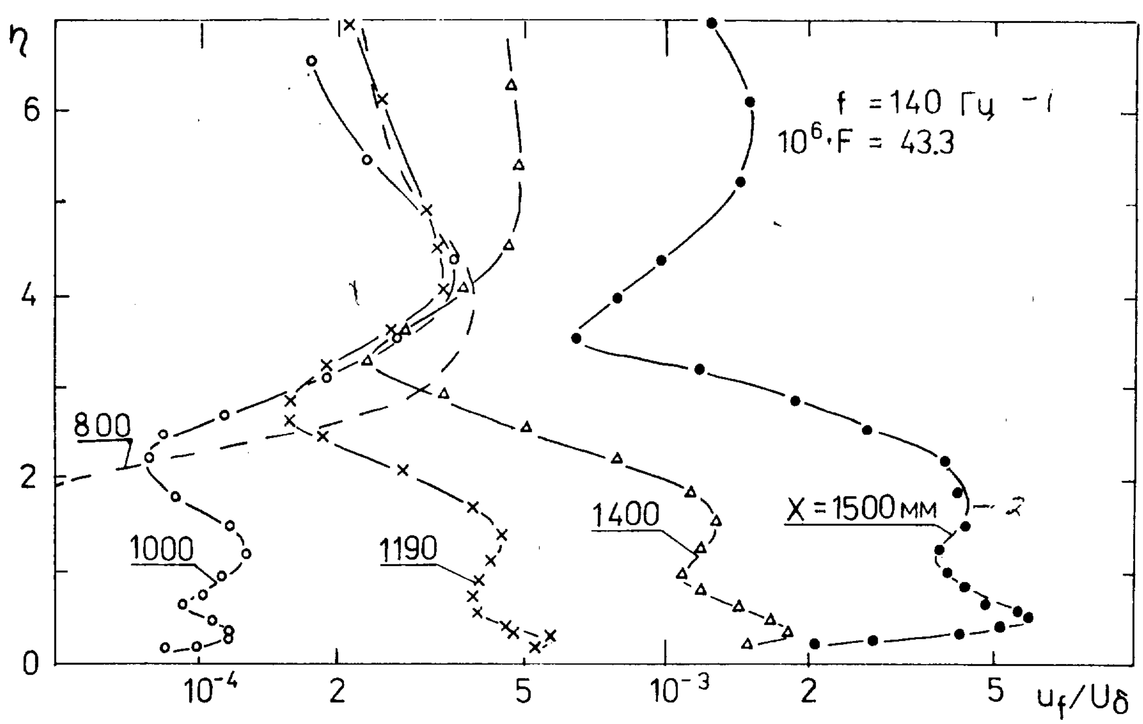
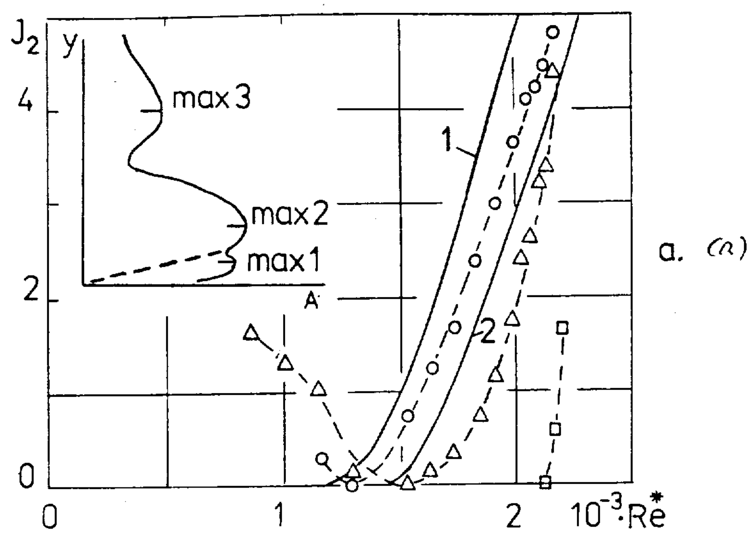


Fig. 11b. 1 - f = 140 Hz; 2 - X = 1500 mm



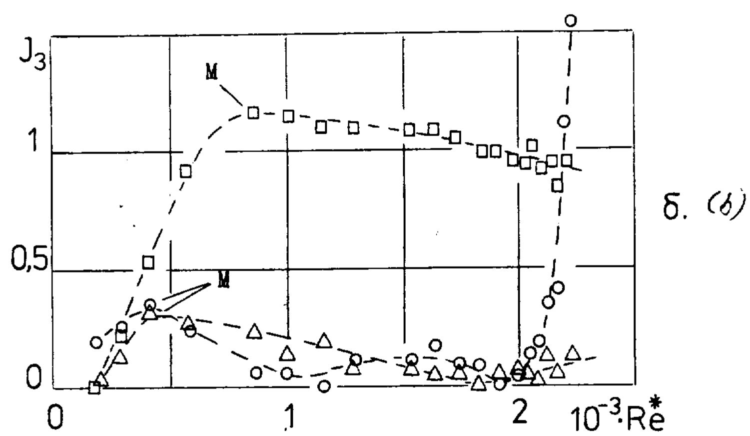


Fig. 12. 1 - $F = 40 \times 10^{-6}$ [17]; 2 - $F = 30 \times 10^{-6}$ [17]; □ - f = 40 Hz, F = $= 12.4 \times 10^{-6}$; Δ - f = 110 Hz, 34×10^{-6}; o - f = 140 Hz, 43.3×10^{-6}